Metal Additive Manufacturing
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Lecture - 09
Laser Based Processes (Part 1 of 2)

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Welcome to the lecture series on metal additive manufacturing. In this lecture we will be trying to cover little bit on basics of laser. Because laser is a very powerful tool which is used for joining or melting powder slash wire metal, metal powder or metal wire to produce the output. We always can think of using electron beam but laser has more flexibility and it is economical.

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Before getting into the lecture let us have a small recap what was covered in the last few lectures. In the last few lectures, we were trying to cover various processes which are falling under metal additive manufacturing. We saw powder bed fusion method, directed energy deposition method, binder jetting method these three are very common.

Then we saw latest emerging metal additive manufacturing process, metal extrusion where in which the metal is mixed with polymer extruded as a wire and then printed. So, material extrusion, material jetting and sheet lamination method. This material extrusion is quite a common process in polymers which is called as fuse deposition modelling.

So, the same thing is used here. It has better advantages but this process as of today is becoming expensive because the extrusion mixing of polymer and metals is a challenge which we discussed in the last lecture.

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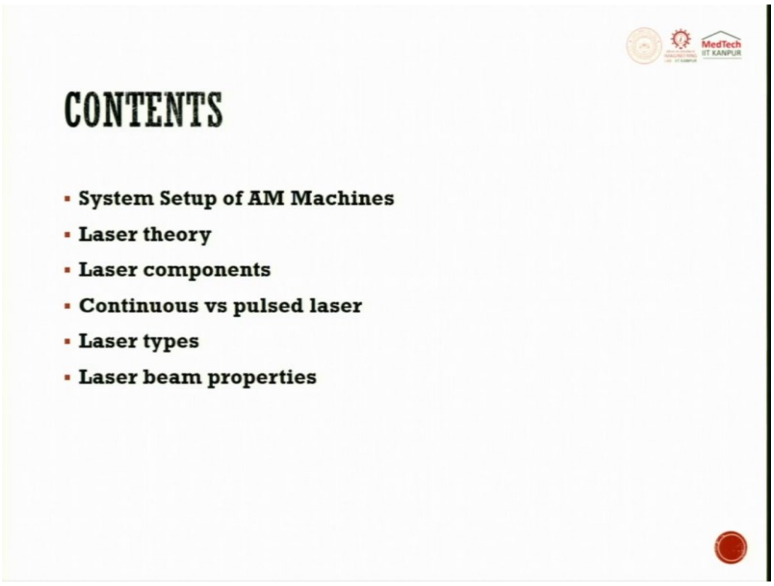

Today we will try to see systems which are involved in additive manufacturing, laser theory, laser components, continuous laser and pulsed laser, laser types and laser beam properties. We will understand the laser fundamentals in this lecture. When we start using laser, we always have to be very precautious on the safety point of view.

Laser when it tries to hit a metal powder or a reflecting surface the laser light reflects and when the reflected light by chance hits your eye it is disastrous. So, when we are working with lasers, be more precautious than normal machining. Today do it yourself is a common thing which is available in YouTube.

People try to look into that and start developing setups but when you do that when you are working with laser, look at the class of the laser and be very cautious to wear laser protective goggles and laser has a very high energy density. So, be very careful when you are using your free hands, also to be very careful with that small caution let us get into the content. Because everybody gets excited after doing this course and thinks can I develop a machine by myself? yes you can, but with a caution.

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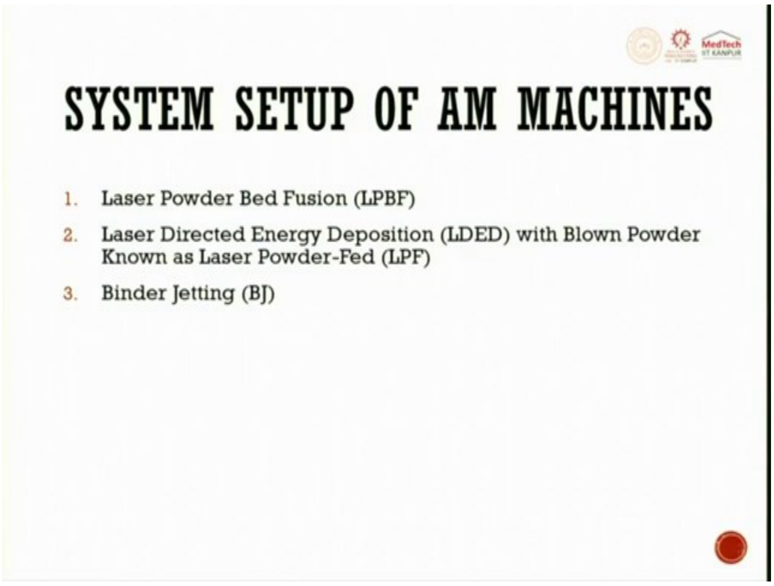

Now let us get into system setup of additive manufacturing machine. So, there are three system setups; one is called as laser powder bed fusion, laser directed energy deposition with blown powder known as laser powder fed, the next one is binder jetting system. These are the most common systems which are used in metal additive manufacturing setups.

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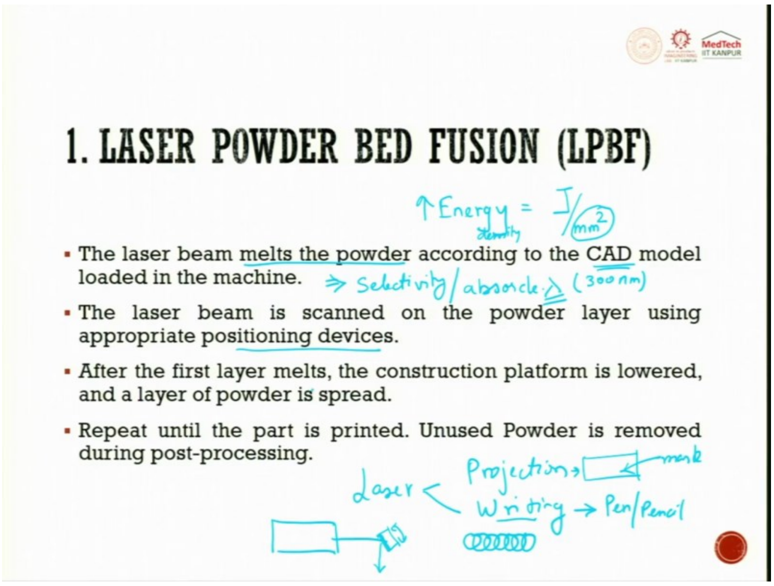

The laser when we talk about laser, laser is a coherent source. This coherent source with focused energy can be used for melting. So, what happens is you have energy which is always in joules. Now this energy, if it is focused on a small area then the energy densities go very high.

So, the advantage of laser is coherent and focused on a small area which gives you the freedom of melting of powder. So, laser beam which is used always tries to melt the powder. The melting of the powder depends on the selectivity that means to say the laser absorbs wavelength λ, interacts with it and then starts doing it.

For example, people use blue laser which has a wavelength close to less than 300 nm. So, this interacts very well with copper. If you use a green laser you might or might not get, and when you use a red laser it will not try to produce a good quality output.

So, the laser wavelength is very important and the power is important to melt the powder. The melting of the powder is not like casting which happens all through, it is done selectively whatever information you have given in the CAD model. Generally, the laser has two approaches laser has projection approach and writing approach.

Projection approach means the laser beam is passed through a mask and the mask information whatever is there is trying to get projected on the surface. It can be a metal surface, it can be a polymer surface but since our focus is more towards metal we will try to keep metal. So, one layer of mask information is given in the mask.

So, now laser is projected through this it falls on the bed, powder bed where the object is getting built and all of them melt in one shot the other way around is we write, writing is like your pen or pencil writing.

So, in your pen or pencil writing what we do is a stylus is moved on top of a surface, the laser tries to move as spots, these spots try to overlap and they try to form a line and moment it forms a line, you can try to generate hatch patterns, through this we try to get a layer formed.

So, laser can be used for projection technique, the laser can be used as writing technique predominantly in metals we use only writing techniques. So, that means to say the laser scans on top of the powder bed. So, that is what I said here the laser beam is scanned on the powder layer using appropriate positioning devices. Now it is very clear.

Now how do I move this spot. You can have laser fixed or the bed fixed if you keep the bed fixed the laser moves right, the laser writes. So, how does a laser write? So, here what happens is the laser from the source is allowed to meet a positioning device or it is trying to hit at a mirror, this mirror will try to focus, this can swivel in x-y plane. So, it will sweep and try to take that spot on top of the bed.

So, appropriate positioning devices can be used to do it. After the first layer melting is done the construction platform is lowered and a layer of powder is spread this gets repeated. So, you try to get the final output.

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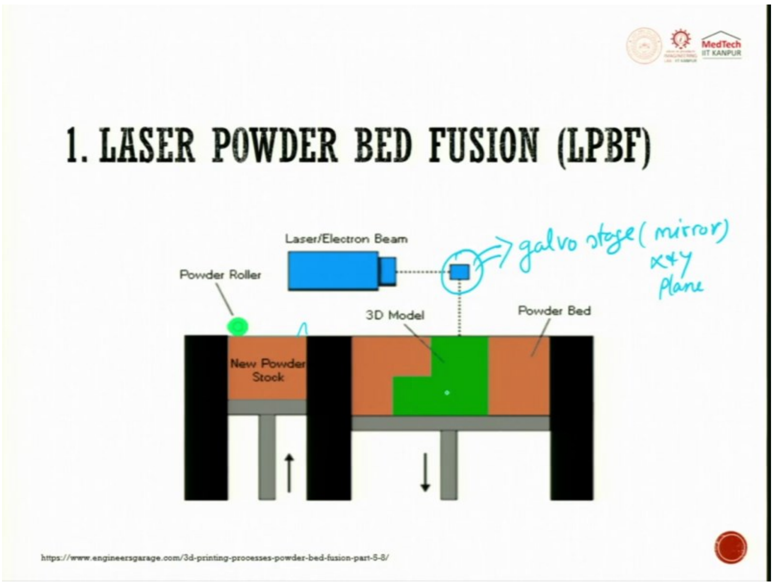

So, this is what we have discussed. For new powder, we have recoater blade is there or your roller is there. So, it rolls there will be a heap this will spread on top of it and you see the model is getting developed. So, this one is called as galvo stage. Galvo stage gives you to write on top of a very large area by just moving the mirror in the x-y plane.

Mirror is in the x-y plane so, you try to get the final output since it is trying to hit at the powder so a lot of free powder will be there which will be removed and extracted and is used for recycling. So, you see the model here, you see the new powder stock and you see the powder bed stock here.

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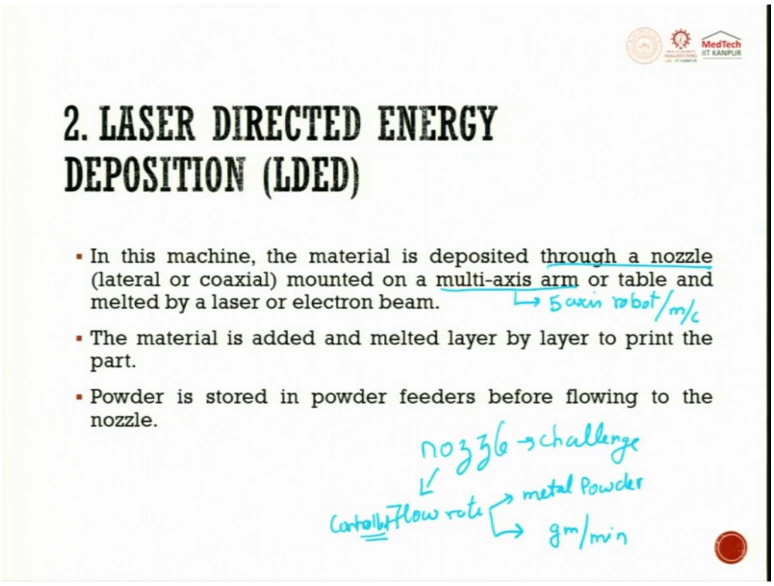

So, when we talk about laser directed energy in this machine, the material is deposited through a nozzle. So, here in this machine you need to have a nozzle. The designing of the nozzle is a challenge. Why? Because through this nozzle you always have a flow rate, flow rate of metal powder is nothing but we can say g/min or mg/min, whatever it is you can try to do it.

So, here we should try to have a controlled flow so that it tries to exactly drop and then you try to melt it. If more amount of flow is there, then improper melting will happen there will be a melt powder and then a solid powder without melt. So, that is why I said controlled flow rate should be there.

So, then this powder will pass through the nozzle and then it will pass coaxially to the laser then the laser will melt and it will try to deposit. And it is mounted on a multi axial movement you can have today a five-axis robot or a machine to do this operation. Nozzle getting fed through five axis you get it or a table which melts by the laser and electron beam. The material is added and melted layer by layer the powder is stored in a powder feeder because the flow in the nozzle has to happen.

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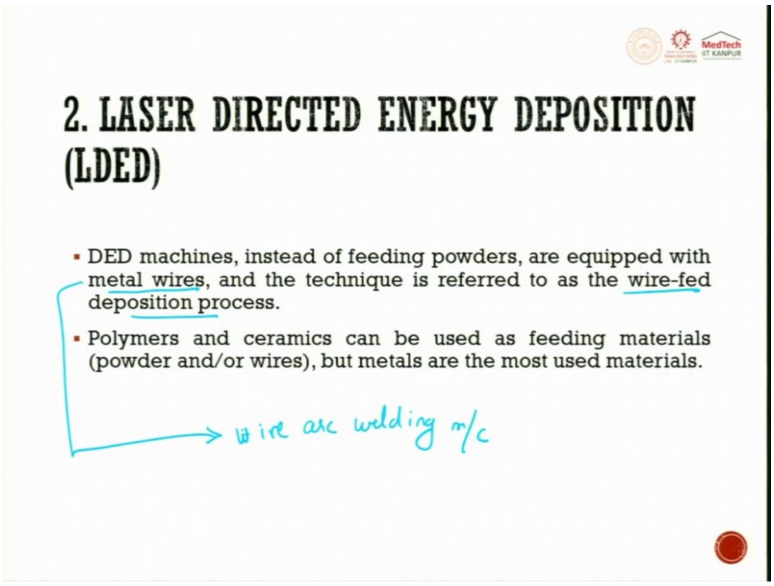

DED machines instead of feeding powder is also equipped for feeding metal wires. So, if you want to look at the analogy you can look at it like a wire arc welding machine it will be like that only. So, wire arc welding machine is you have this wire, which tries to continuously feed.

So, that you can start welding a very large area or try to develop a very good output. So, a metal wire continuously is fed and then it is melts and it tries to grow into 3d object and the technique is referred as metal or wire arc feed, feed deposition process.

Polymers and ceramics also can be fed using this mechanism. So, polymers are also made as wires and in the same way you can also try to make ceramic, you can also try to have a blend of metal ceramic or metal polymer. You can do all these things to get your output, but by enlarge here when we talk about it is going to be only wire.

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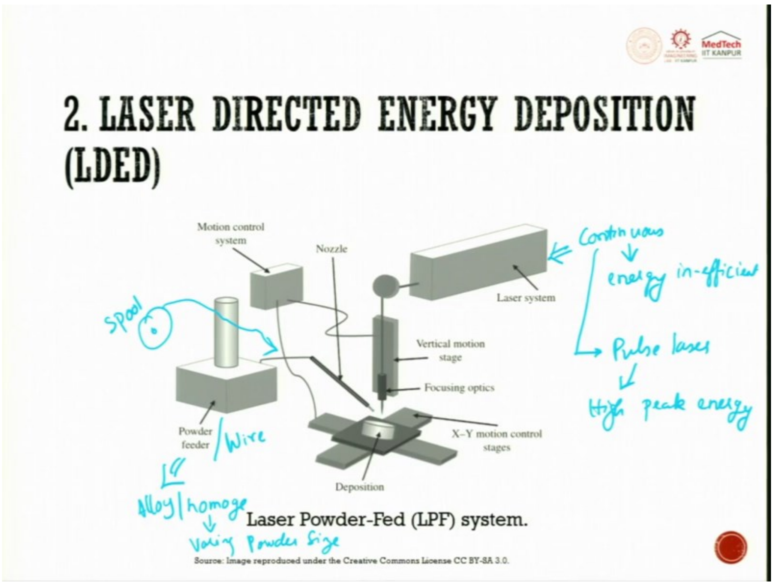

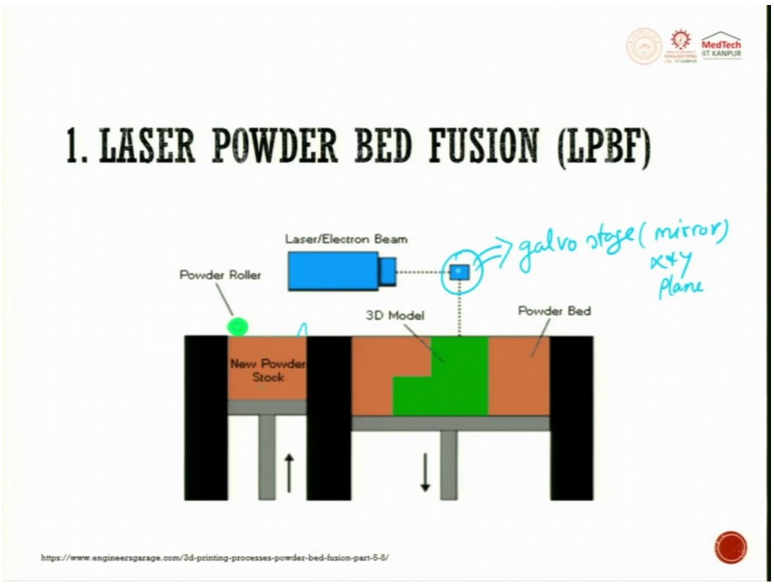

So, this is what we were talking about. So, you can see here the laser is coming and the wire is fed. So, this wire what will happen is you can have a nozzle which is there. So, this instead of powder we can also have wire, it will have a spool, this spool will be connected here, this is a spool, wire spool or you can have a metal powder.

So, the interesting part is you can have alloy powder or you can have a homogeneous powder and again in homogeneous you can have varying powder size depending upon your requirement whatever you want you can try that these are all the benefits which metal additive manufacturing gives when the product is developed.

So, you try to take a spool, this spool is fed and then through a nozzle and when it comes here there is a laser which hits here predominantly. These lasers will be continuous but if you use it will always be energy inefficient. So, people have started using pulsed laser because pulsed laser comes with very high peak energy.

So, this can melt and then it can be deposited. So, you can have coaxially two nozzles feeding on the side then the powder coming in the front. So, it gets deposited, you have a x-y stage where the stage moves. The laser is constant in powder bed you can have this galvo where the galvo can sweep.

But here the laser is kept constant this is what I was trying to say laser can be kept constant, the work piece can move or the laser can move and the work piece is kept constant both combinations are useful. And when you keep the laser constant and then try to develop it, you get better output but again depending upon the process parameters and the condition.

So, here instead of the entire setup, you can try to take it to a machine where it is five axis. So, today we use five axis robots. And these robots are used very well for two things; one for repair and second for refurbishment. It is exhaustively used, point number one, second thing is wherever there is a complex job it is done, third thing is today there are even metal bridges which are built in Europe just by metal additive manufacturing through this process you can do Google and find it out.

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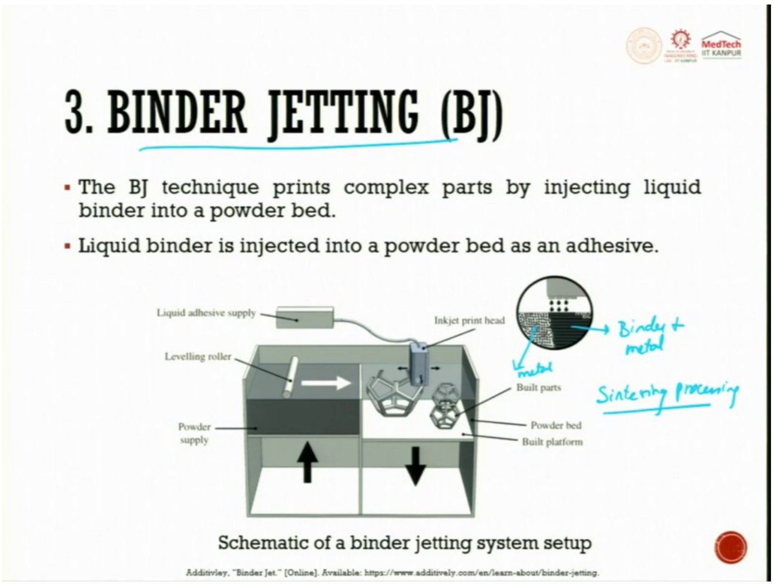

So, binder jetting we already saw. The binder jetting technique prints complex parts by injecting liquid binder into the metal powder. So, this is how it is. So, this will be the metal powder this will be the binder plus metal powder you see the color change.

So, it only joins and then it tries to adhere, moment it adheres then you have a green part you try to take the green part to a sintering machine, first it removes the polymer or first wash it and then try to take it for sintering. So, here predominantly it goes for sintering process. So, here it is very simple you have the liquid container injecting the binder on top of a work piece.

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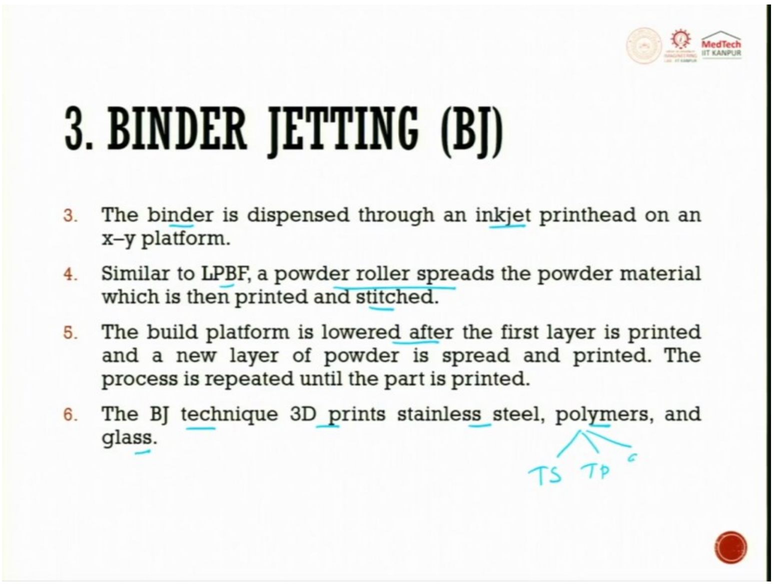

So, the process is explained. Binder is dispensed through an inkjet print head, similar to laser powder bed fusion, powder roller spreads the powder which is then stretched, the platform is lowered, the next layer is done. The binder jet technique 3d printing of stainless steel, polymers and glass is also done today. Again, in polymers you have thermosets polymer, thermoplast polymer, and you have elastomers. So, predominantly these two are done by binder jetting process.

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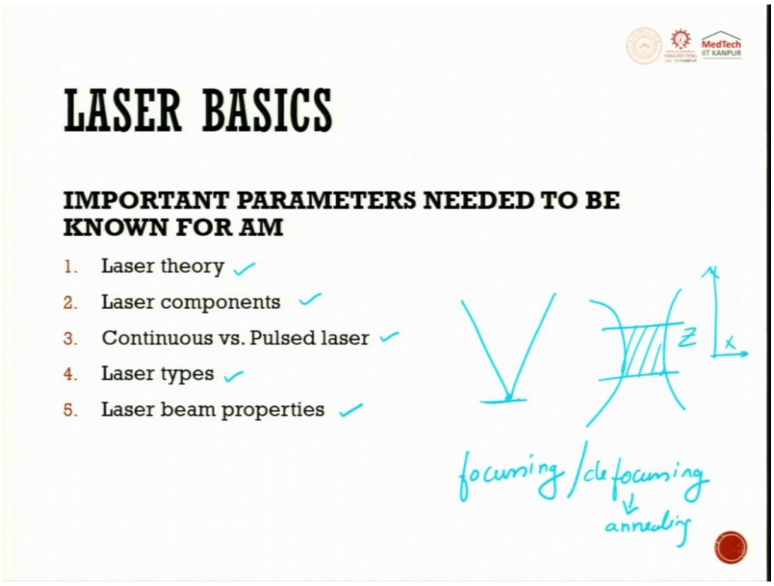

Now let us try to understand this laser because the laser is the heart of the machine. So, then you can try to dictate the process today what is happening, new era of exotic materials are coming. So, for this you do not have a standard additive manufacturing machine.

So, what you do is you try to take powder and then you try to play with the laser parameters to get the best out of it. So, the important parameters need to be known for AM is little bit of laser theory, laser components, the types of laser, here types of laser and then I will try to talk here laser types in terms of wavelength and then finally the laser beam properties.

The laser beam properties are very important because we always try to say if the light hits at a spot and then you try to get, this is only the focal point you say but what happens is, you always have something called as a waste.

So, anywhere in this area you can keep the object to get the best performance. I am trying to draw in terms of this is z direction and this may be x direction. So, you have a length, generally we assume it as a plane but this is a volume, this might be very slow and very small. So, within this if you keep the laser gets focused and while doing metal additive manufacturing you can play with this focusing and defocusing.

So, wherever you would like to have an annealing operation a small heat treatment has to be you just move the either the laser or the bed little bit up and down you go for defocusing and you get an annealing operation. Once you start focusing, you start getting the sintering process or the melting process.

So, these are some of the fundamentals you should understand because when you try to use even an existing very good performance metal additive manufacturing machine, once you get the quality output you should be able to infer where was the problem and how will you sort it out. So, for that also you need to understand the basics of laser.

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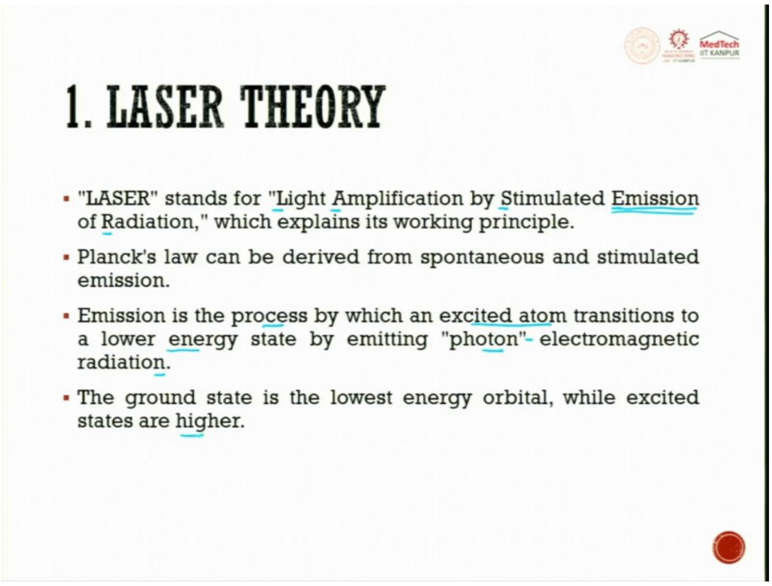

Laser stands for light amplification by stimulated emission of radiation. Planck’s law can be derived from the spontaneous and simultaneous emission. Emission is nothing but a process by which an excited atom transitions to a lower level by emitting photons-electromagnetic radiation, emission is a process. The ground state is called as the lower energy orbital while the excited state is called as the higher one we will see that in detail in the next slide.

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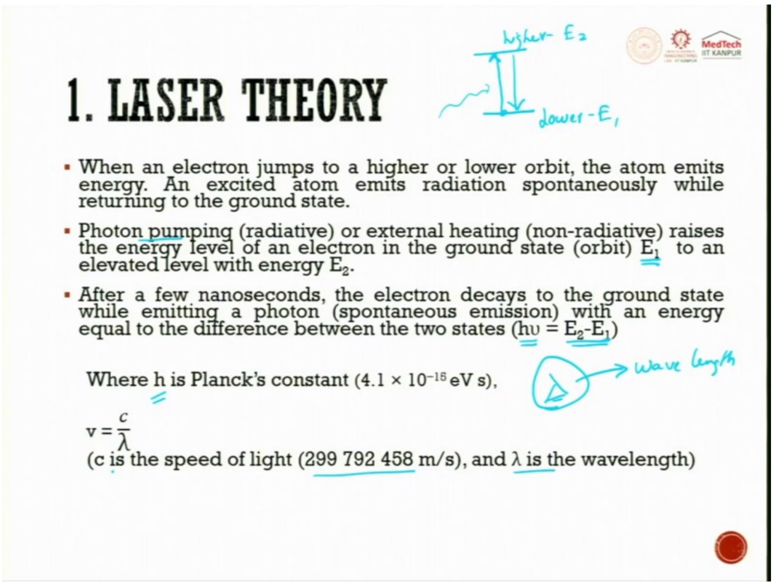

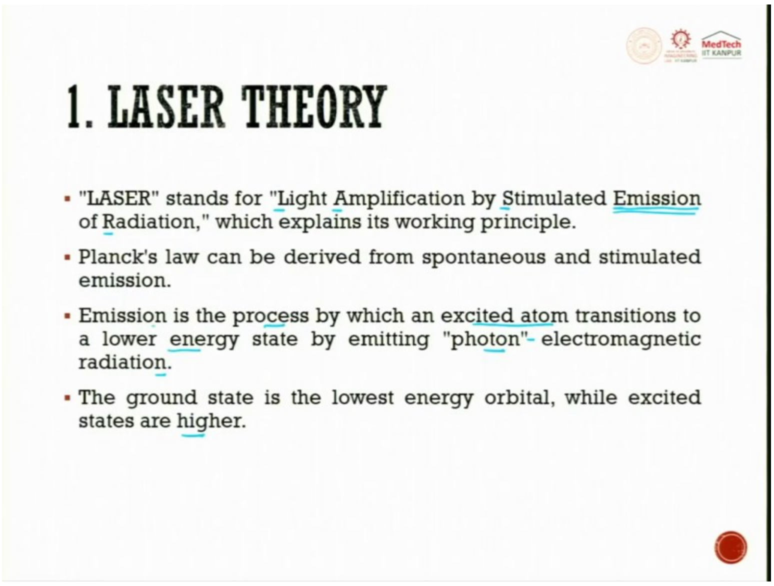

When an electron jumps so this is a lower level, this is a higher level, you have an atom here this, when you try to hit it with a photon this gets excited. So, from lower to higher it cannot stay in the higher for a longer time. So, it will come back to the lower. So, when it is coming back it is called as emission.

So, this is what we described here emission is a process by which an excited atom transitions to a lower level state by emitting photons. When it comes down it has to release energy. So, that is what is called as photons, what are photons, a packet of energy is called as photons generally photons are talked in light related things.

So, when an electron jumps to the higher or the lower orbit the atom emits energy. Because energy can neither be created nor be destroyed, it can only be transformed. So, from here it goes there from there it comes down, an excited atom emits radiation spontaneously while returning to the ground state.

So, when it comes down, when it is decaying, when it is coming down from higher to lower there is a spontaneous emission, the photon pumping or external heating. What is pumping? Something has to give the energy. So, that it goes from here to here that is called as photon pumping.

Photon pumping or external heating raises the energy level of an electron in the ground state to the elevated state which is E1 to E2. After a few nanoseconds, the electron decays to the ground state while emitting a photon spontaneously that is why it is called as spontaneous emission with an energy equivalent to the difference between the two stages. ($h\upsilon = E2-E1$), Where h is Planck's constant ($4.1 \times 10{-}15$ eV s), $\upsilon = c/\lambda$ (c is the speed of light (299 792 458 m/s), and λ is the wavelength).

So, you see there is a relationship of λ which comes into existence. This λ is very important which is nothing but the wavelength. You can always wonder why do you buy a blue laser why do I buy a green laser when you try to buy an additive manufacturing machine the vendor says this machine is wonderful because it has a green laser.

What is a big deal of green laser is here λ, in turn with respect to photon energy which helps you in melting. So, this λ is very important. So, if you see Planck's constant it is always there. So, here υ we have defined it like this.

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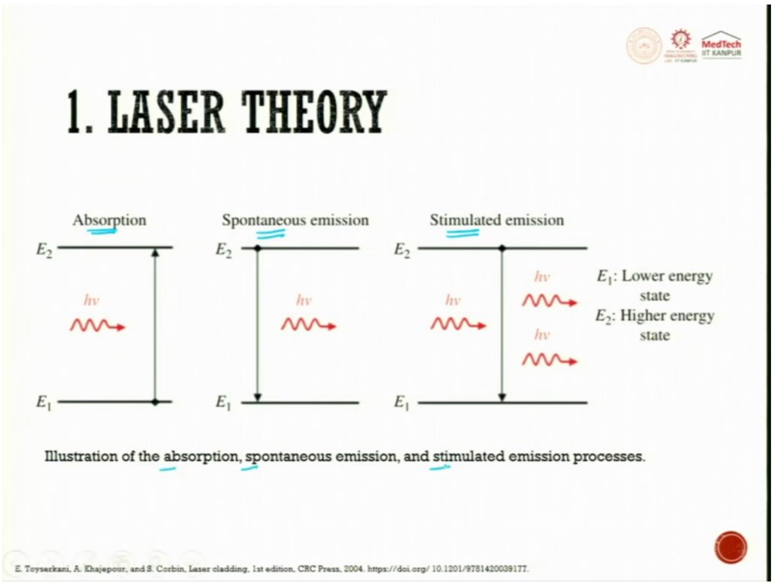

So, this is what I have explained. So, just one quick recap of it, from E1 it goes to E2 this is what is the pumping happening. So, this is called as the absorption phase the next one is called as the spontaneous emission. So, from the top it drops down, when it drops down it tries to give out, hυ that is spontaneous.

Stimulated means what hits and what comes out is of the same wavelength so that is called as stimulated emission. So, you have illustration of absorption, spontaneous and stimulated emission process. So, E1 or E2 are the energy states.

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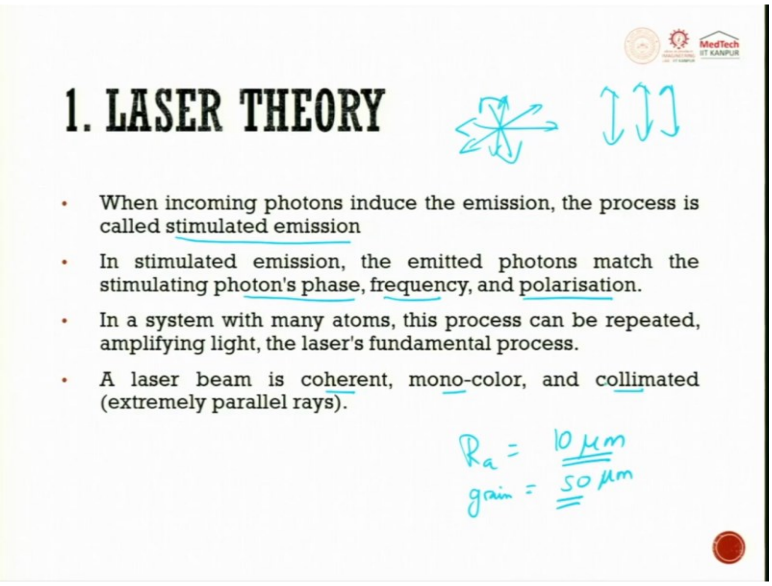

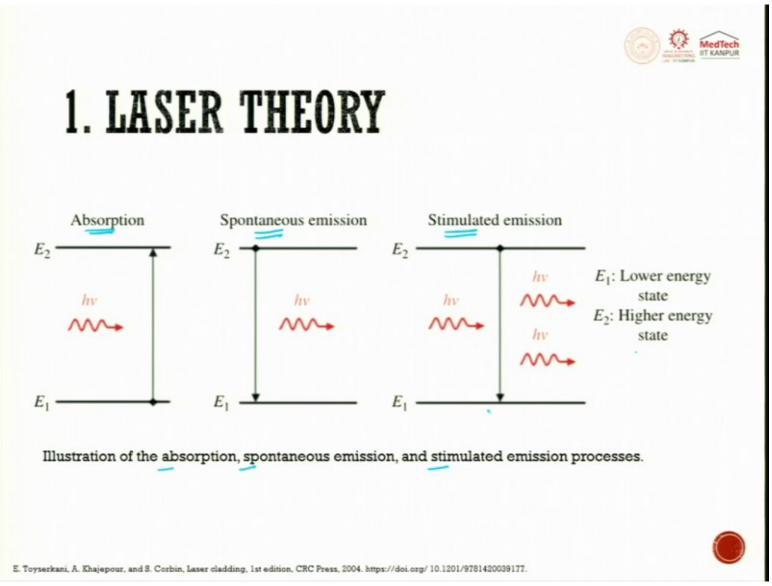

When the incoming photon induces the emission, the process is called as stimulated emission. In stimulated emission the emitted photon matches with the stimulated photon phase in terms of phase, frequency and polarization.

Polarization means all of them are directed in one direction when the light comes. Now you will have it, that will go in all directions, you will all try to bring in only one direction. So, that is called as polarization. Why? Because this polarization will try to help me in focusing and when we are talking about metal additive manufacturing and we are talking about roughness of 10 μ. So, grain size of around about 50 μ, the laser focusing spot should be close to this.

Then only, you can get a good quality output in a system with many atoms. The process can be repeated amplifying light and the laser fundamental process finally in a nutshell the laser beam is coherent mono color and collimated. So, this gives you a freedom of focusing.

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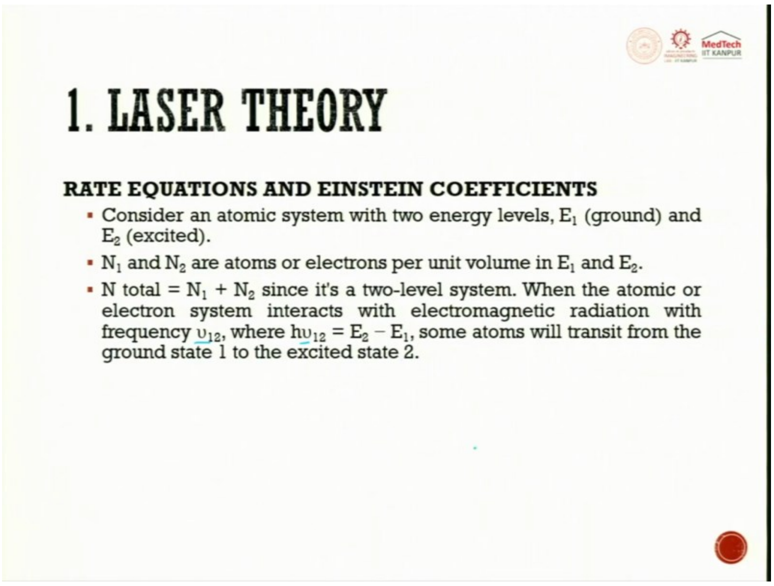

So, the rate equation and the Einstein coefficient which are always used. So, consider an atomic system with two energy levels E_1 and E_2 the number of atoms present are N_1 and N_2 are the atoms or the electrons per unit volume in E_1 and E_2 the total $N=N_1+N_2$ since it is two level system, you can also have three level system, four level system.

When the atomic or the electron system interacts with electromagnetic radiation with a with frequency υ_{12}, where $h\upsilon_{12} = E_2 - E_1$, some atoms will transit from the ground state 1 to the excited state 2. So, this is the rate equation and the Einstein coefficient we cover here.

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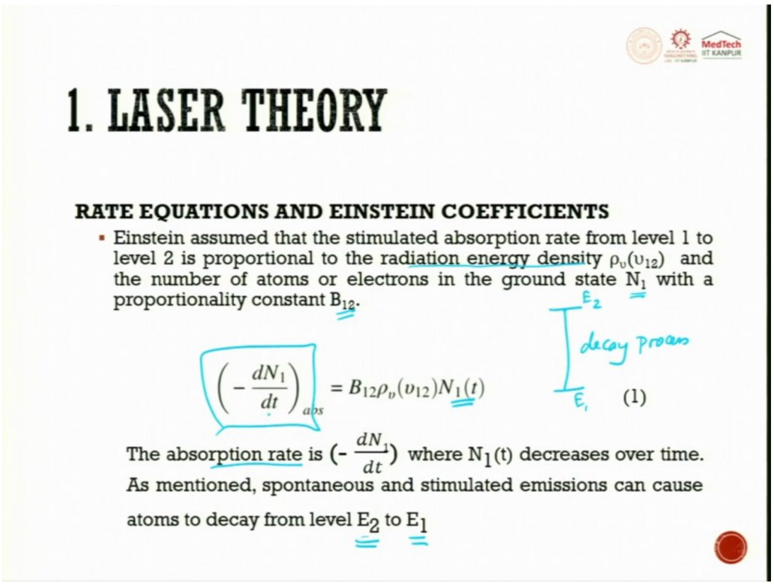

Einstein assumed that the stimulated absorption rate from level 1 to level 2 is proportional to the radiation energy density and the number of atoms or electrons in the ground state N_1 which is proportional to a constant called B_{12}.

So, this is what the equation is:

$$\left(-\frac{dN_1}{dt}\right)_{abs} = B_{12}\rho_\upsilon(\upsilon_{12})N_1(t)$$

The absorption rate is ($-\frac{dN_1}{dt}$) where $N_1(t)$ decreases over time. As mentioned, spontaneous and stimulated emissions can cause atoms to decay from level E_2 to E_1.

It is called as decaying process, and here you can try to find out the absorption rate with respect to time.

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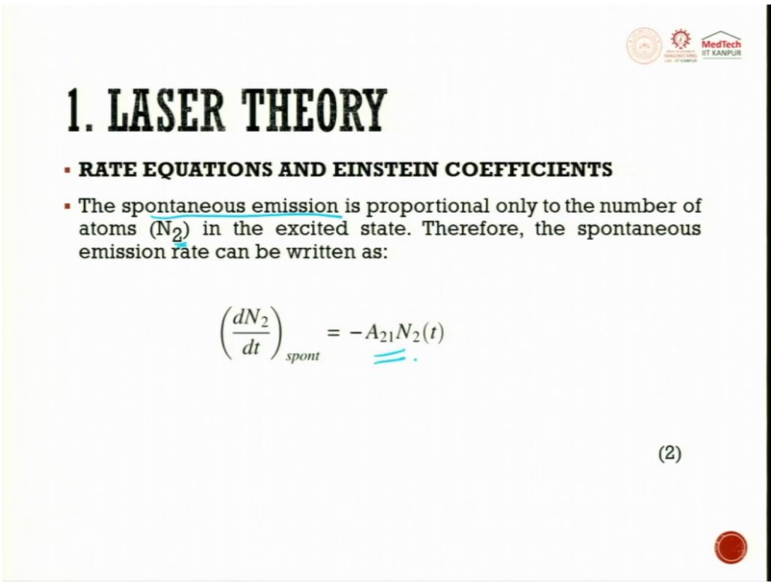

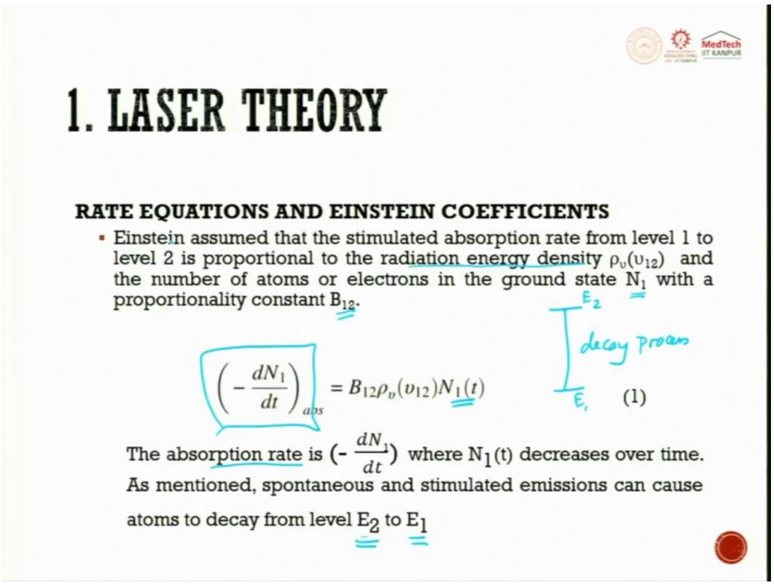

The spontaneous emission is proportional only to the number of atoms in N_2. So, this one we were trying to talk about stimulated absorption rate. Now, we are trying to talk about spontaneous emission rate, which is proportional to the number of atoms N_2 in the excited state therefore the spontaneous emission rate can be written as:

$$\left(\frac{dN_2}{dt}\right)_{spont} = -A_{21}N_2(t)$$

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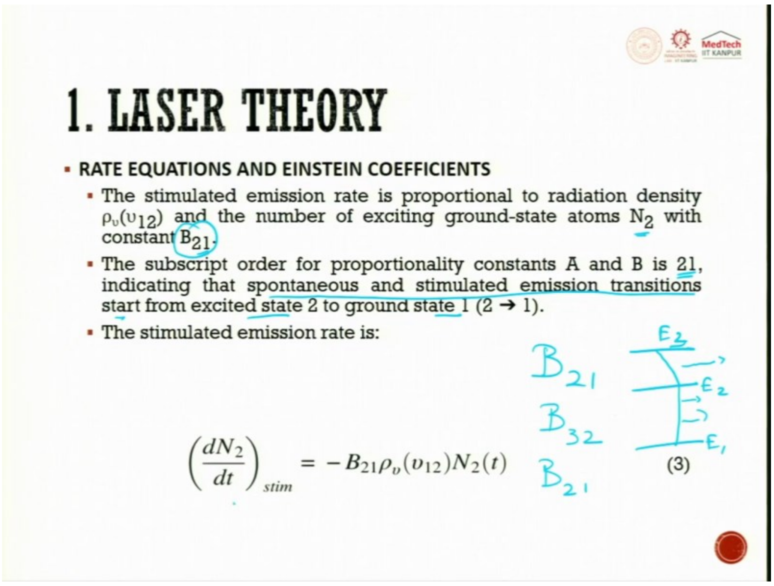

So, this stimulated emission rate is proportional to radiation density. Radiation is what comes out. Radiation density and the number of excited ground state atoms N_2 with respect to a constant is called B_{21}. The subscript order for proportionality constant A and B is 21 indicating that spontaneous and simultaneous emission transition starts from excited state 2 to the ground state 1 that is why we call this constant B_{21}. The stimulated emission rate is:

$$\left(\frac{dN_2}{dt}\right)_{stim} = -B_{21}\rho_\upsilon(\upsilon_{12})N_2(t)$$

Otherwise, it will be if you have a 3-level system it will be B32 and then you will say B21. So, that means to say you are stopping at one level and then you are falling it down to the next level and from here you are going down. So, here what happens is, there is more time it takes more time to decay from one level to the other level.

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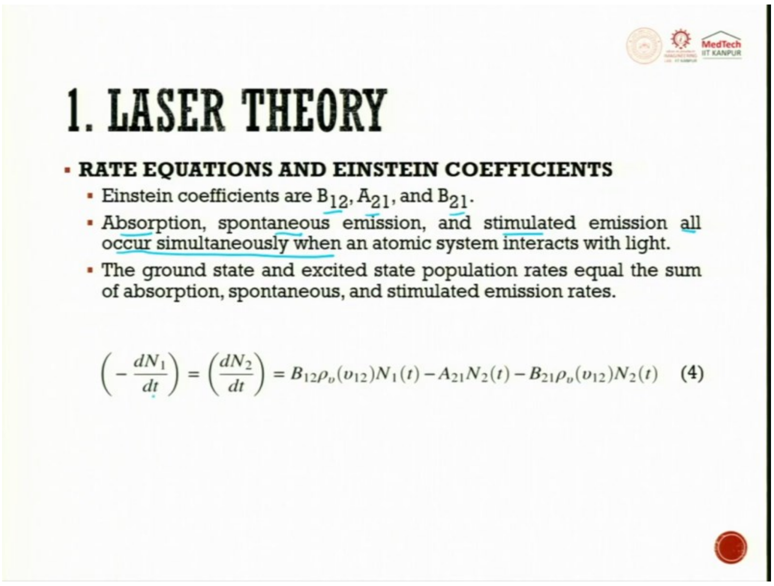

So, now B_{12}, A_{21} and B_{21} are all Einstein coefficients which can be directly pulled out from some literature you can get these constants, absorption, spontaneous emission and stimulated emission all occur simultaneously when an atomic system interacts with light. The ground state and the excited state population rate equals the sum of absorption, spontaneous emission and stimulated emission.

$$\left(-\frac{dN_1}{dt}\right) = \left(\frac{dN_2}{dt}\right) = B_{12}\rho_{\upsilon}(\upsilon_{12})N_1(t) - A_{21}N_2(t) - B_{21}\rho_{\upsilon}(\upsilon_{12})N_2(t)$$

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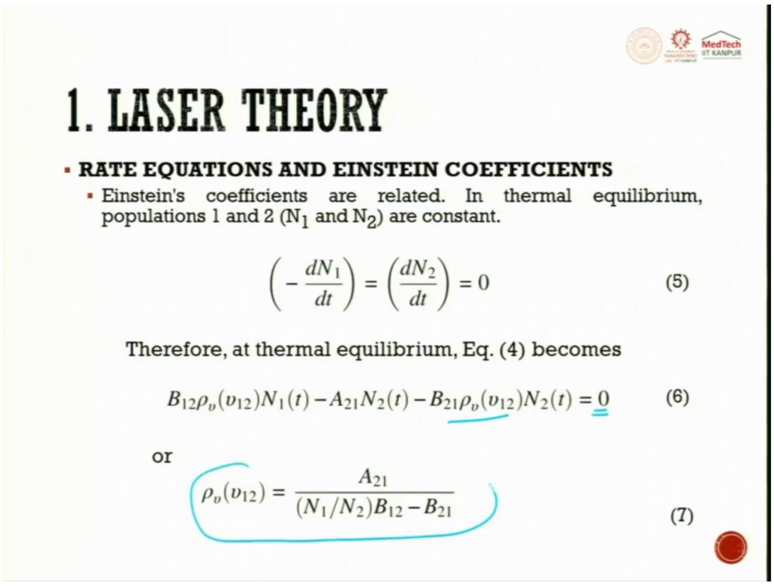

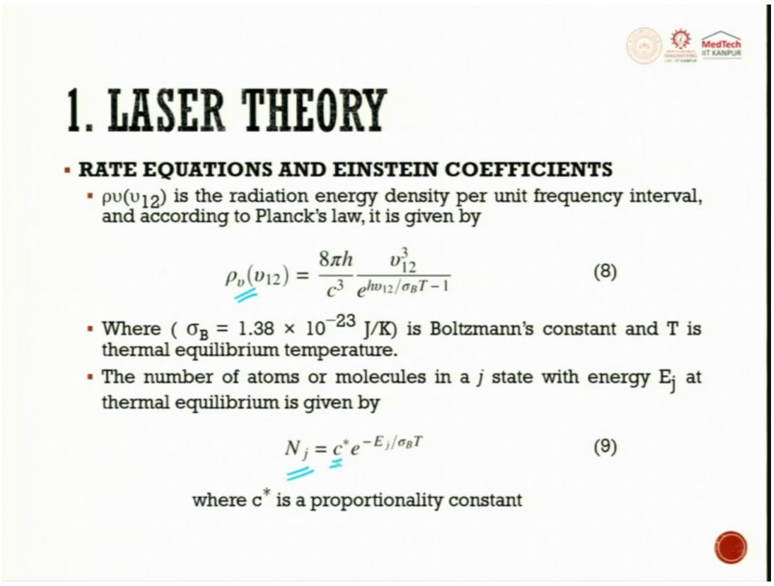

So, now Einstein coefficients are related. In thermal equilibrium, N_1 and N_2 are equal and are constants.

$$\left(-\frac{dN_1}{dt}\right) = \left(\frac{dN_2}{dt}\right) = 0$$

We take the previous equation whatever is given here to become like this which is equal to 0 and from here we reiterate and we try to get the formula like this.

$$B_{12}\rho_v(v_{12})N_1(t) - A_{21}N_2(t) - B_{21}\rho_v(v_{12})N_2(t) = 0$$

$$\rho_v(v_{12}) = \frac{A_{21}}{(N_1/N_2)B_{12} - B_{21}}$$

So, ρ_v is nothing but the radiation density. So, radiation energy density per unit frequency interval and according to Planck's law it is given by this.

$$\rho_v(v_{12}) = \frac{8\pi h}{c^3}\frac{v_{12}^3}{e^{hv_{12}/\sigma_B T} - 1}$$

Where ($\sigma_B = 1.38 \times 10^{-23}$ J/K) is Boltzmann's constant and T is thermal equilibrium temperature.

The number of atoms or molecules in a *j* state with energy E_j at thermal equilibrium is given by:

$$N_j = c^* e^{-E_j/\sigma_B T}$$

Where C * is a proportionality constant.

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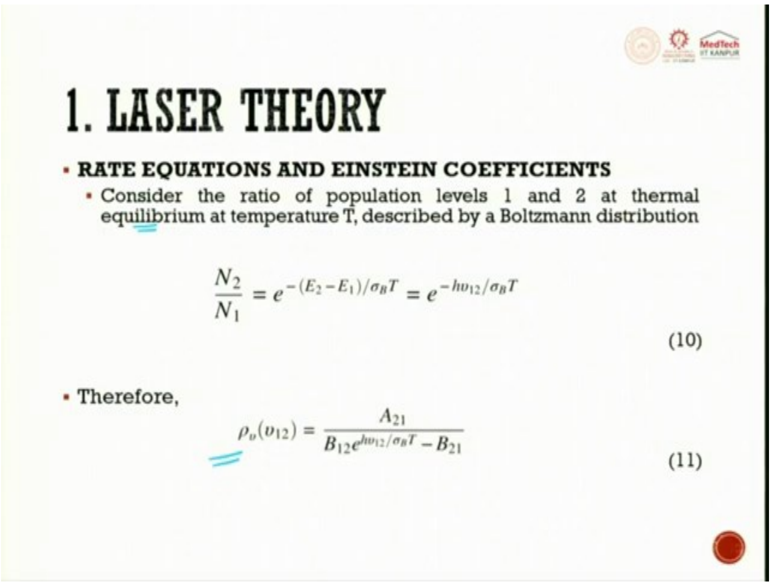

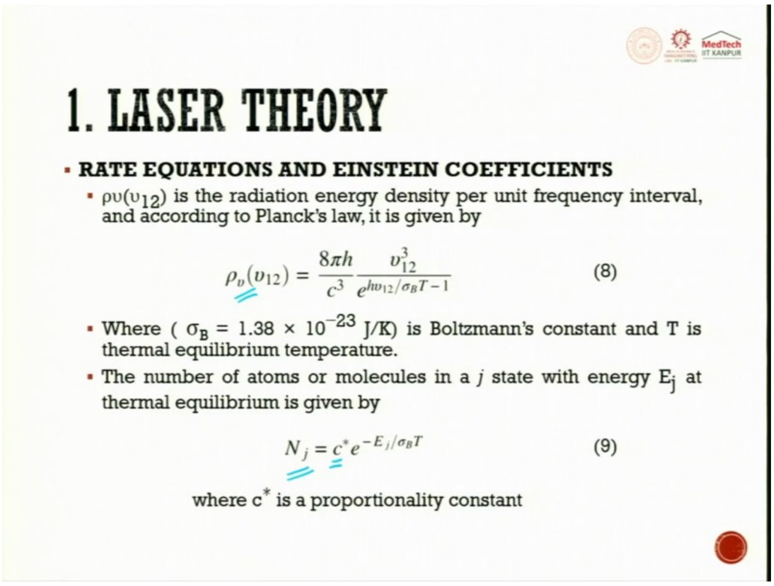

So, considering the ratio of population level 1 and 2 at thermal equilibrium temperature t it is given by:

$$\frac{N_2}{N_1} = e^{-(E_2 - E_1)/\sigma_B T} = e^{-h\upsilon_{12}/\sigma_B T}$$

Therefore,

$$\rho_\upsilon(\upsilon_{12}) = \frac{A_{21}}{B_{12}e^{h\upsilon_{12}/\sigma_B T} - B_{21}}$$

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1. LASER THEORY

- **RATE EQUATIONS AND EINSTEIN COEFFICIENTS**
  - Einstein's coefficients are related. In thermal equilibrium, populations 1 and 2 (N_1 and N_2) are constant.

$$\left(-\frac{dN_1}{dt}\right) = \left(\frac{dN_2}{dt}\right) = 0 \tag{5}$$

Therefore, at thermal equilibrium, Eq. (4) becomes

$$B_{12}\rho_\upsilon(\upsilon_{12})N_1(t) - A_{21}N_2(t) - B_{21}\rho_\upsilon(\upsilon_{12})N_2(t) = 0 \tag{6}$$

or

$$\rho_\upsilon(\upsilon_{12}) = \frac{A_{21}}{(N_1/N_2)B_{12} - B_{21}} \tag{7}$$

1. LASER THEORY

- **RATE EQUATIONS AND EINSTEIN COEFFICIENTS**
  - Consider the ratio of population levels 1 and 2 at thermal equilibrium at temperature T, described by a Boltzmann distribution

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/\sigma_B T} = e^{-h\upsilon_{12}/\sigma_B T} \tag{10}$$

- Therefore,

$$\rho_\upsilon(\upsilon_{12}) = \frac{A_{21}}{B_{12}e^{h\upsilon_{12}/\sigma_B T} - B_{21}} \tag{11}$$

1. LASER THEORY

- **RATE EQUATIONS AND EINSTEIN COEFFICIENTS**
  - If we now compare Eqs. (7) and (11), it derives as

$$B_{12} = B_{21} \tag{12}$$

  - This result shows that the absorption and stimulated emission processes are equivalent.
  - Moreover, we obtain that

$$A_{21} = \frac{8\pi h\upsilon_{12}^3}{c^{*3}}B_{21} \tag{13}$$

  - Asserting that absorption and spontaneous emission are proportional to each other

So, now we compare equation 7 with respect to 11, and then we try to get

$B_{12} = B_{21}$. This result show that absorption and stimulated emission process are equivalent. So, then we get to know more about A21:

$$A_{21} = \frac{8\pi h v_{12}^3}{c^{*3}} B_{21}$$

So, you see all the proportions we have discussed in the previous slides asserting that the absorption and spontaneous emission are proportional to each other.

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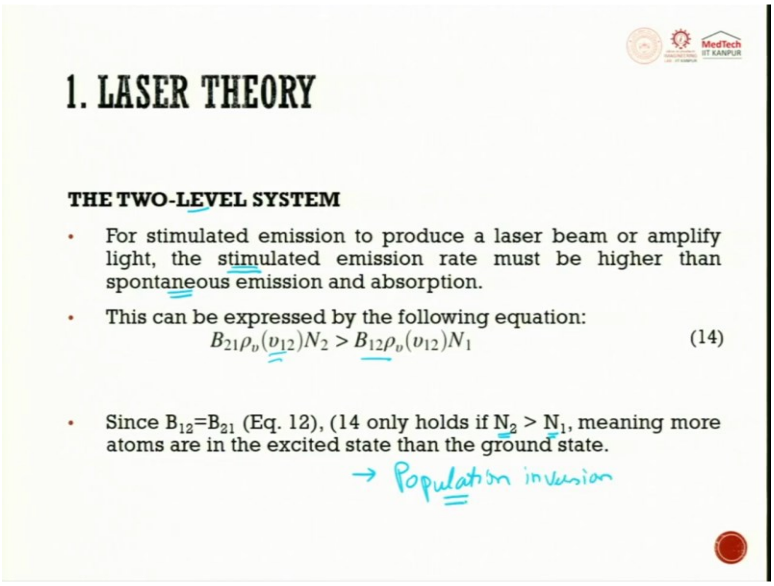

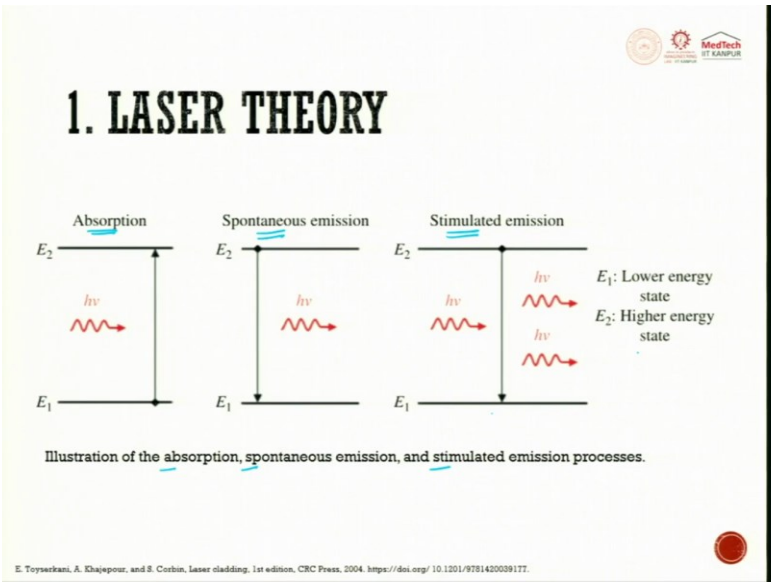

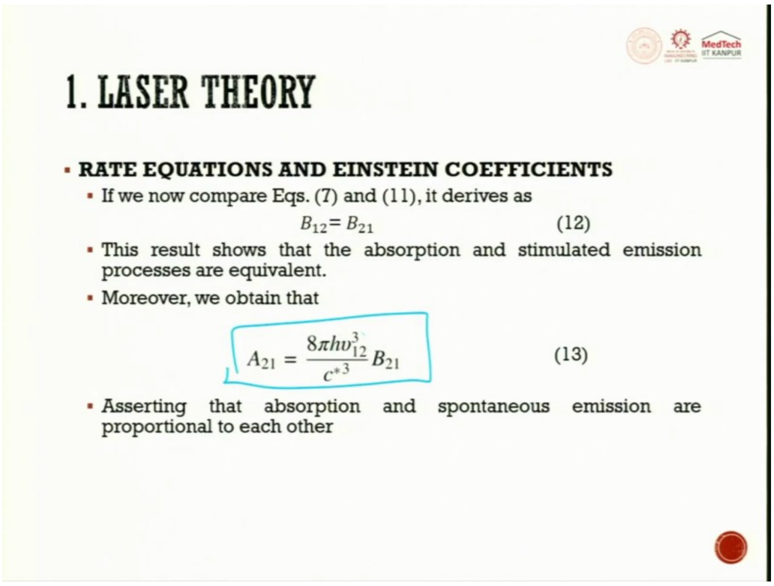

So, I was talking to you about two level system and three level systems. In two level system, for stimulated emission to produce a laser beam or amplifying light the stimulated emission rate must be higher than the spontaneous emission.

$$B_{21}\rho_{\upsilon}(\upsilon_{12})N_2 > B_{12}\rho_{\upsilon}(\upsilon_{12})N_1$$

Since $B_{12}=B_{21}$, the above equation only holds if $N_2 > N_1$, meaning more atoms are in the excited state than the ground state. This is population inversion.

So, let us go back and see what is stimulated emission and what is stim, this is stimulated and spontaneous. Spontaneous means instantaneously what is released. Stimulated emission means you are stimulating; you are getting the base back plus one more energy which you are getting that is stimulated.

So, this is what we are trying to cover here we are trying to talk about stimulated emission. So, the stimulated emission to produce a laser beam or amplify light or stimulated emission rate must be higher than the spontaneous emission and absorption.

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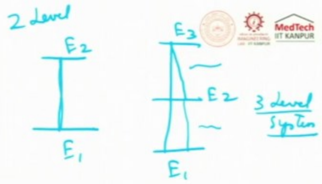
1. LASER THEORY



THE TWO-LEVEL SYSTEM

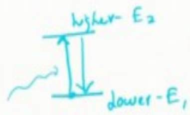
- Population inversion causes this. According to Eq. (10), At thermal equilibrium, the population density relation between levels 2 and 1 is given by the Boltzmann distribution, and N_2 must be lower than N_1 ($N_2 < N_1$) because $h\upsilon_{12}/\sigma_B T$ is positive.
- In thermal equilibrium, population inversion cannot occur.
- The rate equation for this type of system is given by

$$\left(-\frac{dN_1}{dt}\right) = \left(\frac{dN_2}{dt}\right) = B\rho_\upsilon(\upsilon_{12})[N_1(t) - N_2(t)] - AN_2(t) \quad (15)$$

1. LASER THEORY

- "LASER" stands for "Light Amplification by Stimulated Emission of Radiation," which explains its working principle.
- Planck's law can be derived from spontaneous and stimulated emission.
- Emission is the process by which an excited atom transitions to a lower energy state by emitting "photon" electromagnetic radiation.
- The ground state is the lowest energy orbital, while excited states are higher.

1. LASER THEORY

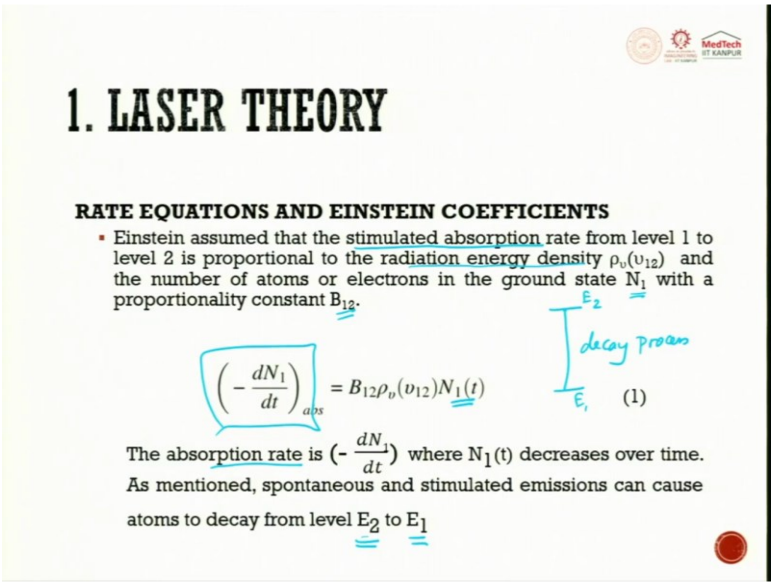


- When an electron jumps to a higher or lower orbit, the atom emits energy. An excited atom emits radiation spontaneously while returning to the ground state.
- Photon pumping (radiative) or external heating (non-radiative) raises the energy level of an electron in the ground state (orbit) E_1 to an elevated level with energy E_2.
- After a few nanoseconds, the electron decays to the ground state while emitting a photon (spontaneous emission) with an energy equal to the difference between the two states ($h\upsilon = E_2 - E_1$)

Where h is Planck's constant (4.1×10^{-15} eV s),

$$v = \frac{c}{\lambda}$$

(c is the speed of light (299 792 458 m/s), and λ is the wavelength)



So, two level system and three level system. The energies of two level system is E_1 E_2, while three level system will be E_1 E_2 E_3. So, here spontaneously it falls down. So, here it goes up, goes down here, one emission will come, from here it will come. So, here your efficiency goes like this is two level and this is three level.

Nowadays you also have four level systems how do they do it they try to do doping of the glass or they try to have optical fiber doped, they add materials ingredients. So, now laser efficiency has gone up very high.

See I have now covered so many things slowly, if you walk through I have covered Planck's law right then I talked about Boltzmann constant then Planck's constant and Einstein. So, almost all these constants and distributions are all getting integrated into one thing called as laser. People who do this course I want them to understand little bit of these basics because this will try to give you a better understanding what is happening even today. The continuous lasers have an efficiency of 20%, why 20? why cannot it go for 80? it has a thermal management system.

So, what stops them can I shrink the size of the metal additive manufacturing? what puts the stoppage? if you understand this, then you can understand that nicely that is why I am taking pains and going through all these things. Distribution N_2 must be lower than N_1, then the thermal equilibrium population inversion cannot occur. So, the rate of equation for this type of system is given as this.

$$\left(-\frac{dN_1}{dt}\right) = \left(\frac{dN_2}{dt}\right) = B\rho_\upsilon(\upsilon_{12})[N_1(t) - N_2(t)] - AN_2(t)$$

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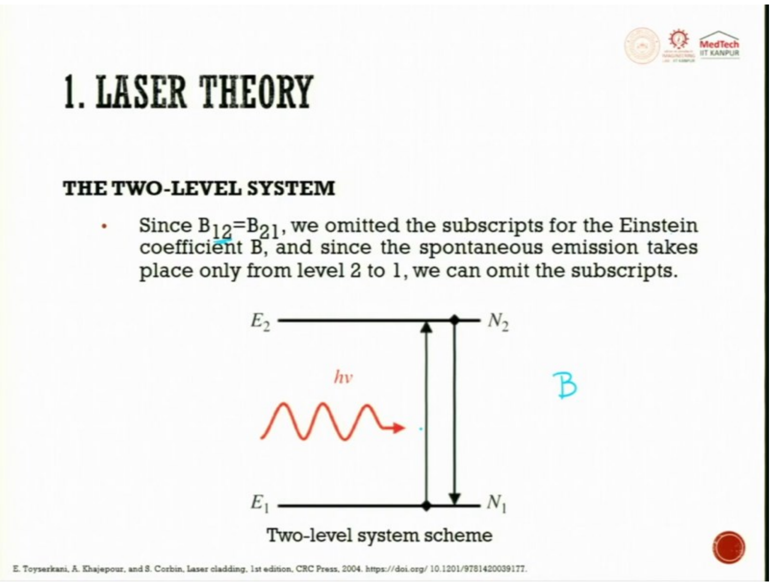

So, this is a two-level system. Since B_{12} and B_{21} are equal, we omit the subscript for the Einstein coefficient B and since the spontaneous emission takes place only from level 2 to 1 we can omit the subscript one to two or two to one, that is why we write it as B a constant, so this is two level system.

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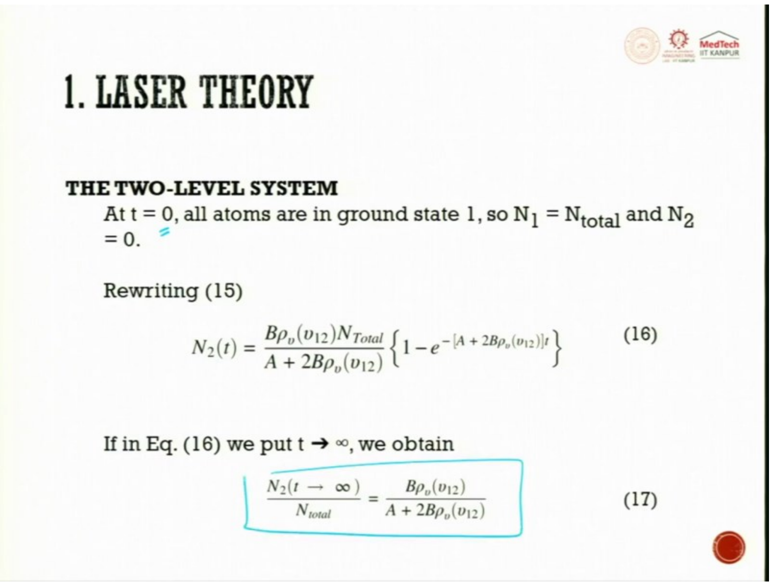

At t=0, all the atoms are in the ground state 1. $N_1 = N_{total}$ and $N_2 = 0$.

$$N_2(t) = \frac{B\rho_\upsilon(\upsilon_{12})N_{Total}}{A + 2B\rho_\upsilon(\upsilon_{12})}\left\{1 - e^{-[A + 2B\rho_\upsilon(\upsilon_{12})]t}\right\}$$

If in the above equation, we put t ➔ ∞, we obtain

$$\frac{N_2(t \rightarrow \infty)}{N_{total}} = \frac{B\rho_\upsilon(\upsilon_{12})}{A + 2B\rho_\upsilon(\upsilon_{12})}$$

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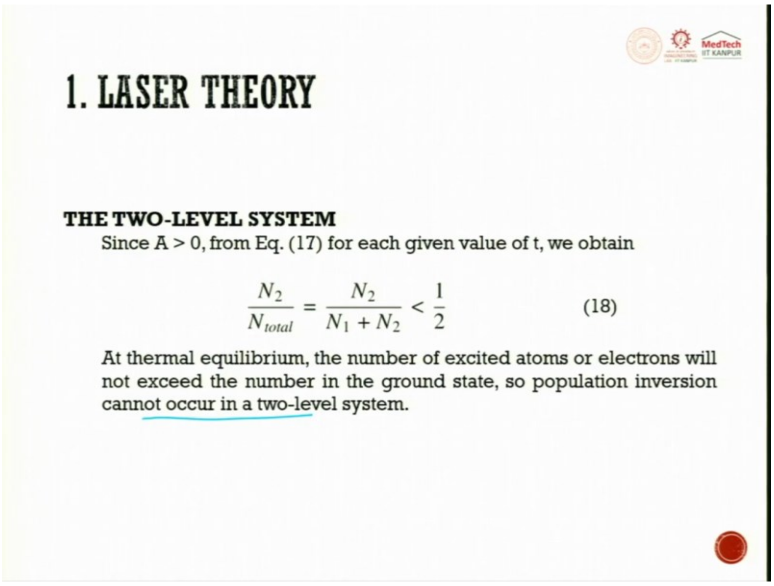

Since A>0. So, for a given value of t we can write it as this.

$$\frac{N_2}{N_{total}} = \frac{N_2}{N_1 + N_2} < \frac{1}{2}$$

At thermal equilibrium the number of excited atoms or the electrons will not exceed the number in the ground state. So, population inversion cannot happen. So, population inversion is a term which we generally use it very liberal but there is lot of science behind it I am just trying to bring all those things to your knowledge.

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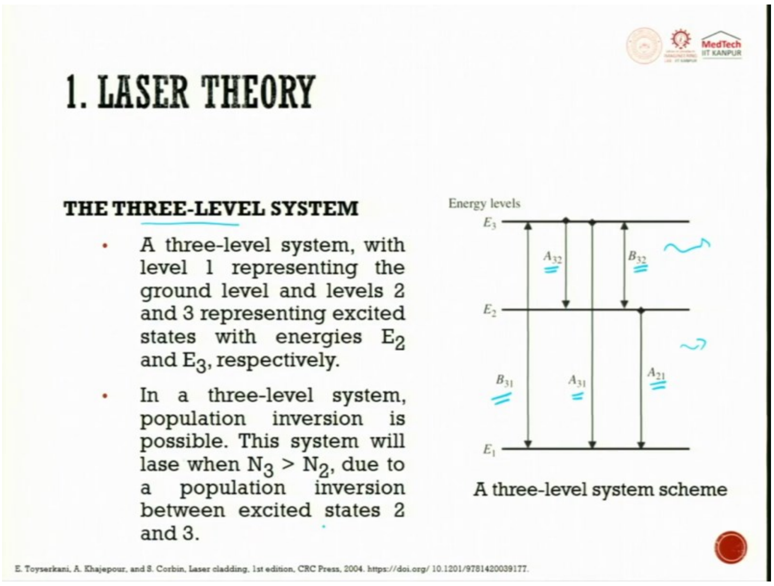

So, as I told you there are three level systems also. In a three level system population inversion is possible. This system will lase when N3 is greater than N2 due to the population inversion between the excited state 2 and 3.

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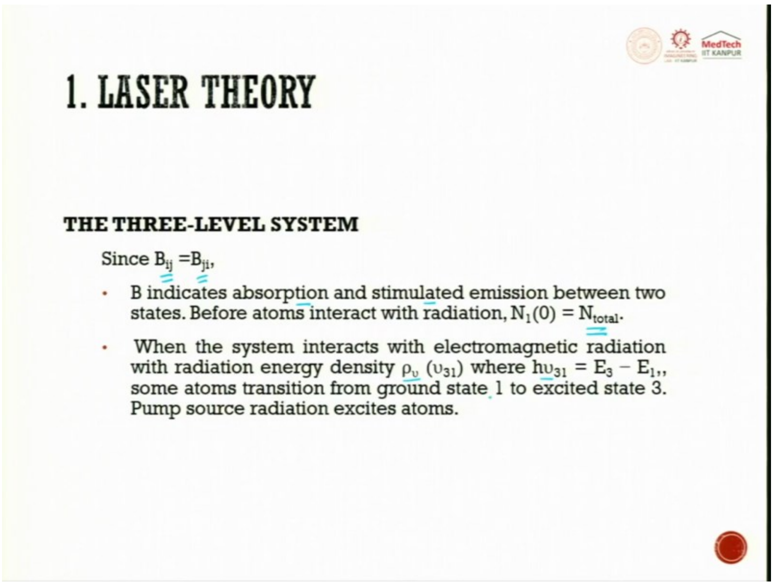

So, here $B_{ij} = B_{ji}$. B indicates absorption and stimulated emission between two states. Before atoms interact with radiation $N_1(0) = N_{total}$. When the system interacts with electromagnetic radiation with radiation energy density, $\rho_\upsilon(\upsilon_{31})$ where $h\upsilon_{31} = E_3 - E_1$, some atoms transition from ground state 1 to excited state 3. Pump source radiation excites atoms.

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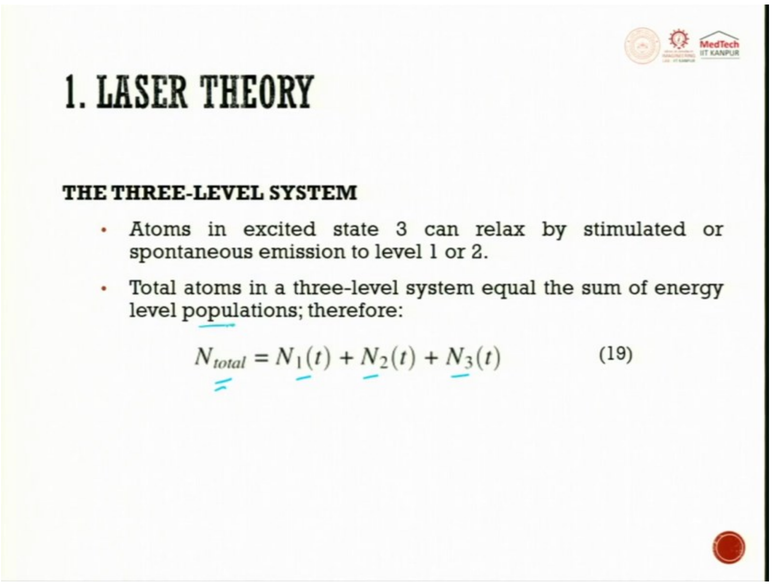

So, now the total is going to be:

$$N_{total} = N_1(t) + N_2(t) + N_3(t)$$

The atom in excited state 3 can relax by stimulated or spontaneous emission to level 1 or 2. The total amount of 3 level system equals the number of energy level population. So, you can see more and more levels you have, more and more emissions you will have.

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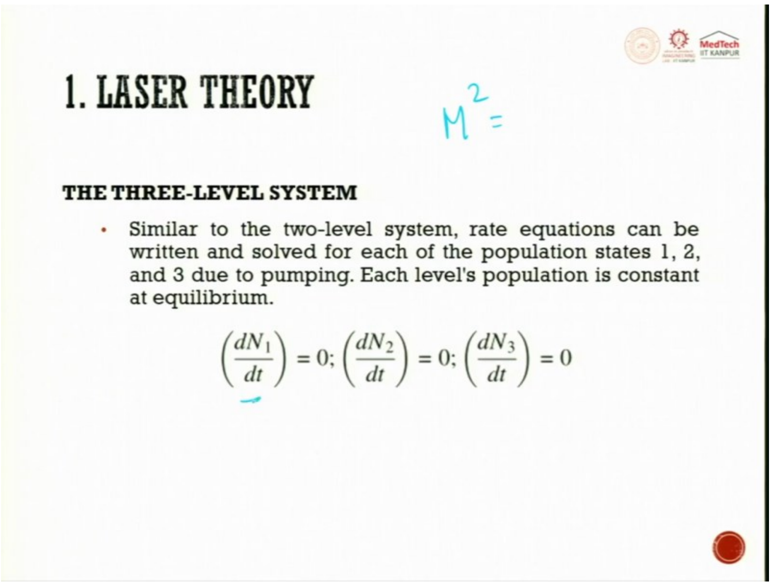

So, this is what is. So, they say when you buy a laser, it is two level laser, three level laser, sometimes they do not even tell you and once you know this you can see why because this in turn directly tries to hit your M^2 value, what is M^2? M^2 tries to talk about the accuracy of your laser.

Similar to the two level system the rate of emission can be written and solved for three level system. For each of the population state 1, 2, and 3 due to pumping each level population is constant at equilibrium. So, you can take dN_1, dN_2, dN_3.

$$\left(\frac{dN_1}{dt}\right) = 0; \left(\frac{dN_2}{dt}\right) = 0; \left(\frac{dN_3}{dt}\right) = 0$$

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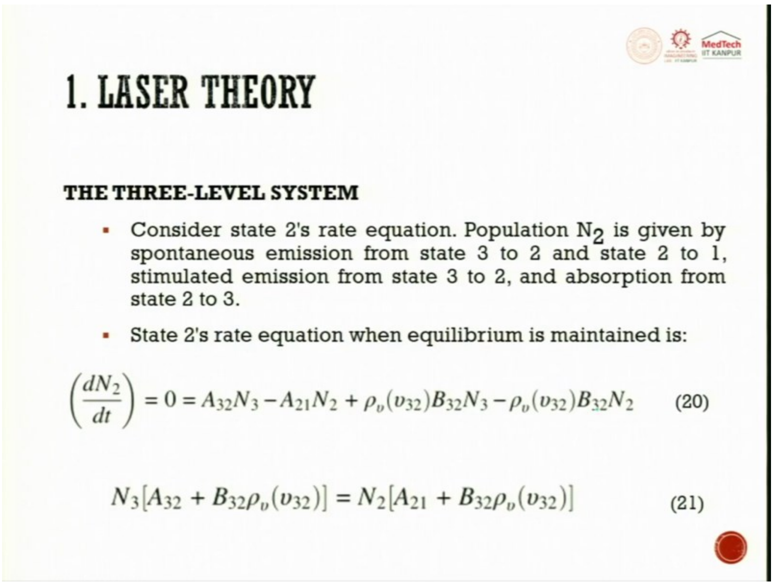

So, three levels. So, the second rate equation is given by the spontaneous emission from state 3 to 2 and state 2 to 1. So, the stimulated emission from 3 to 2 and absorption from 2 to 3. So, the state two rate equation when equilibrium is maintained will be like this:

$$\left(\frac{dN_2}{dt}\right) = 0 = A_{32}N_3 - A_{21}N_2 + \rho_\upsilon(\upsilon_{32})B_{32}N_3 - \rho_\upsilon(\upsilon_{32})B_{32}N_2$$

And you will get two equations by rewriting it.

$$N_3[A_{32} + B_{32}\rho_\upsilon(\upsilon_{32})] = N_2[A_{21} + B_{32}\rho_\upsilon(\upsilon_{32})]$$

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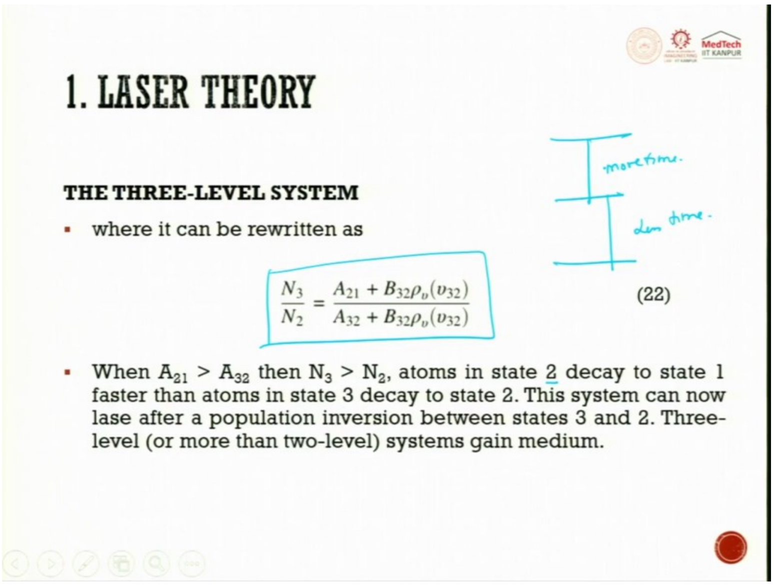

So, N3 will be rewritten like this.

$$\frac{N_3}{N_2} = \frac{A_{21} + B_{32}\rho_\upsilon(\upsilon_{32})}{A_{32} + B_{32}\rho_\upsilon(\upsilon_{32})}$$

So, faster than the atoms in state 3 decay to state 2. So, atoms in the state 2 decays to state 1 faster than the atoms decay from state 3 to state 2. So, for more and more time, more and more emission can happen, three level systems are more than two level systems gain medium.

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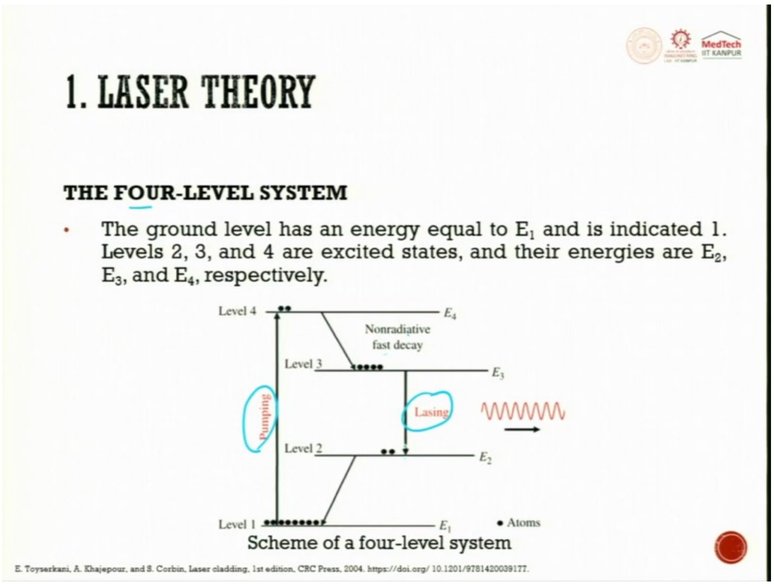

So, you have also four level as I told you. So, from here it gets excited to this level, from here non radiative fast decay happens up to 3. So, from here it goes, lasing action happens here, from here to here it goes down. So, you can see pumping action and lasing action, when it goes to this level. So, here non radiative fast decay will happen, it will try to be more efficient when we use a four level system.

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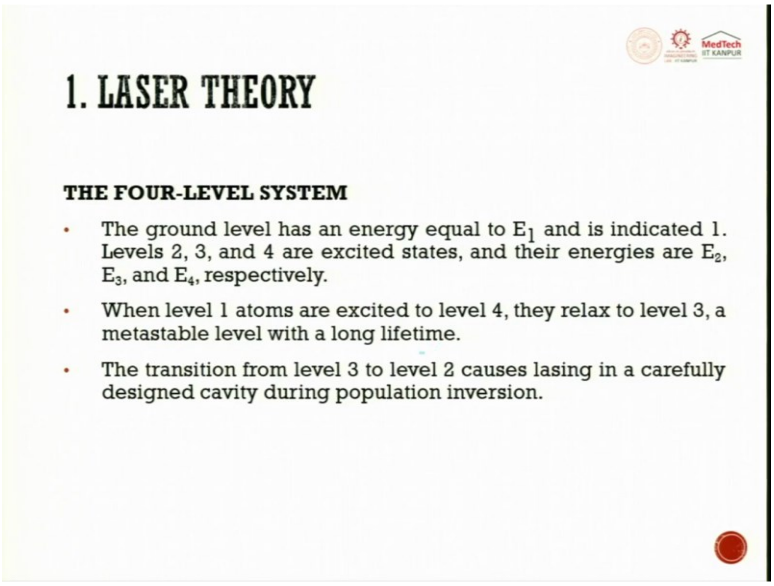

So, the ground level has an energy equivalent to E_1 and is indicated by 1, the levels 2, 3, and 4 are excited states and their energy levels are E_2, E_3, and E_4 respectively. When level 1 atoms are excited to level 4 they relax to level 3 and a meta stable level with a longer lifetime. So, that means to say it has a longer lifetime. From 3 to 2 it causes lasing action and then it tries to come down.

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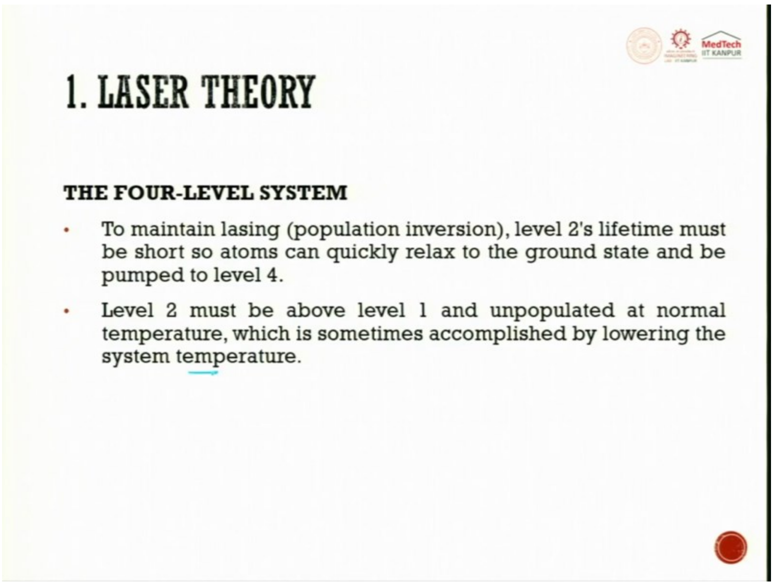

So, to maintain lasing, level 2 lifetime must be shorter. So, atoms can quickly relax to the ground state and go back to the level 4, level 2 must be above level 1 and unpopulated at normal temperature which is sometime accomplished by lowering the system temperature. So, this is where we use heat management as a tool.

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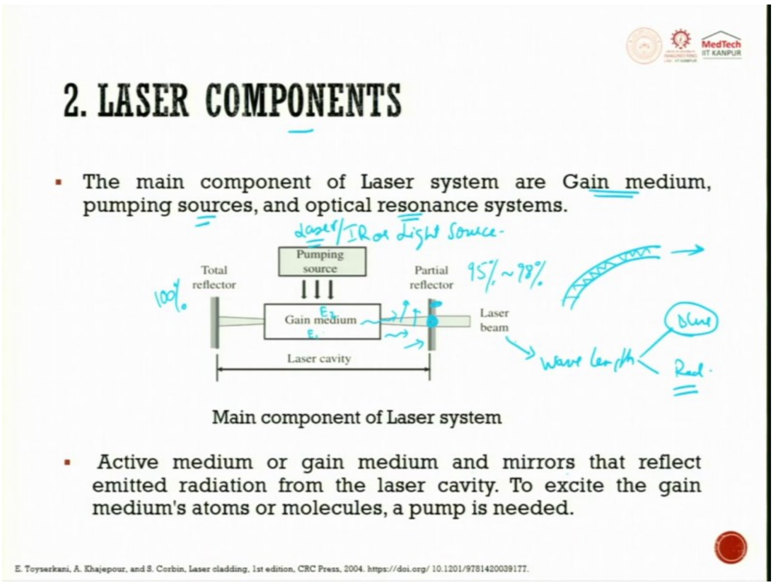

When we try to look at the lasing components, main components of the lasing system are gain medium, pumping source and optical resonance. Optical resonance is nothing but where there is a back and forth movement going on, gain medium means where you try to focus and gain things, pumping source means what tries to excite the ground level.

So, you see generally what will happen in a laser cavity. By the way these are all for schematic explanations. Today we have optical fiber which is used as a lasing gain media and it tries to produce an output. So, things are changing in a very big way. So, fiber lasers are also available today but just for your understanding we will see the schematic diagram. So, that you know the ingredients whatever it is.

So, optical fibers are very small. So, through this also today they are trying to do. So, here they have gratings and this gratings helps for multiple reflections. Let us keep moving here. So, laser cavity means it is assumed that it is a closed cavity, like a box.

So, at one end of the box is total reflection and the other end of the box is partial reflection. Total reflection means it is 100%, partial reflection means it is 95%- 98%. So, here what happens is you will have a medium. So, in this medium you will have all the atoms at the ground level. When the pumping source hits it, the pumping source can be two. It can be a laser itself or you use a IR or any other light source.

When you use a laser whatever comes out, you will have two wavelengths very clearly; one can be say for example blue, the other one can be red and then what will happen is you put a filter for red and you try to get only blue out. It will be very distinctly seen if you put a filter in between and cut it off.

The beauty of laser is you can try to put lenses and you can try to chop off whatever you do not want you try. So, that is the best part of this laser. So, you have a gain media, gain media is a place where all the electrons are in ground state. So, pumping sources hit. So, it moves from E_1 to E_2 or E_3, E_4.

So, now it is getting excited. The moment it is releasing, it releases the photons in all directions. Now in this all directions, they are moved back and forth and once it reaches a level of 98%, all of them in one wavelength then there is an out through which the laser light comes out.

So, the basic components of laser system is gain medium. That is where you have E_1 E_2 and other things what we read till now, pumping source which tries to excite from E_1 to E_2 and resonance to maintain and get all in one particular direction. So, the active media or the gain media are mirrors that reflect emitted radiation from the cavity system. To excite the gain medium, atoms or molecules a pump is used.

So, this is what I have explained to you. So, all these things are there. So, all these things are now shrunk and then they are put into fiber optics. So, you have fiber optic laser. And depending upon the power, this system can be used for very high powers. When you want to have a pulse rating like, very high power, but a continuous power of very low joules, then they go for fiber optic cables.

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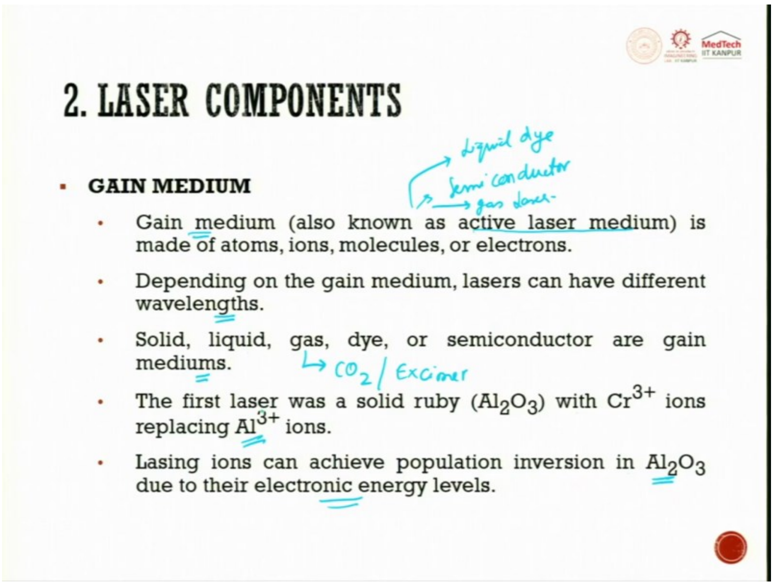

Gain medium, also known as active laser medium is made of atoms, ions, molecules or electrons. Depending on the gain medium, the laser can have different wavelength. So, this is what, so you can have a semiconductor laser, you can have a gas laser, you can have a liquid dye laser, all these things are now the gain medium.

Depending upon the gain media you can try to have different wavelengths, you can have solid, liquid, gas, dye or semiconductor as a media. You have gaseous lasers also. So, for example CO_2 is a gaseous laser, excimer laser all these things are there. The first laser was a solid ruby laser. Alumina with chromium ion replacing aluminium ions, lasing ions can achieve population inversion in alumina due to their electronic energy levels. So, in the first laser was the solid ruby alumina was used with chromium ion replacing the Al_3 ions. E_1 to E_3 E_1 to E_2 you can go.

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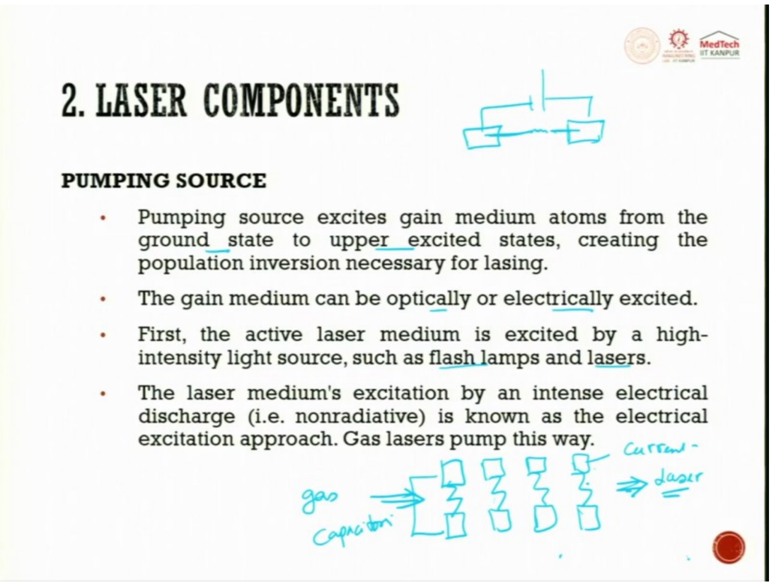

The pumping source excites gaining medium atoms from a ground state to an upper excited state creating population inversion necessary for lasing action. The lasing media can be optical or electrically excited. You can use a very high power and then also you can do like an arc.

So, that is what electrically excited also can be or semiconductor is also an electrical excitement. First the active laser media is excited by a higher intensity light source such as a flash lamp or a laser. The lasing media excitation by an intense electrical discharge is known as electrically excitation approach, the gas pumping this way.

So, what we are trying to say is you will try to have arcs or a capacitor. Bank of capacitor you will have. So, in this bank of capacitors you will try to pass very high current. So, when you pass very high current it creates a spark. Now, you try to pump in gas and what comes out is a laser which is excited. This gas it all gets by the arc, it all gets energized, it tries to create a plasma and then that is further moved and then you have multiple mirrors, then you get an output that finally comes out as a laser.

The laser medium excitation by an intense electrical discharge, this what I said capacitor is known as electrical excitation approach and the gas is moved through it you can have solid or you can have gaseous laser also.

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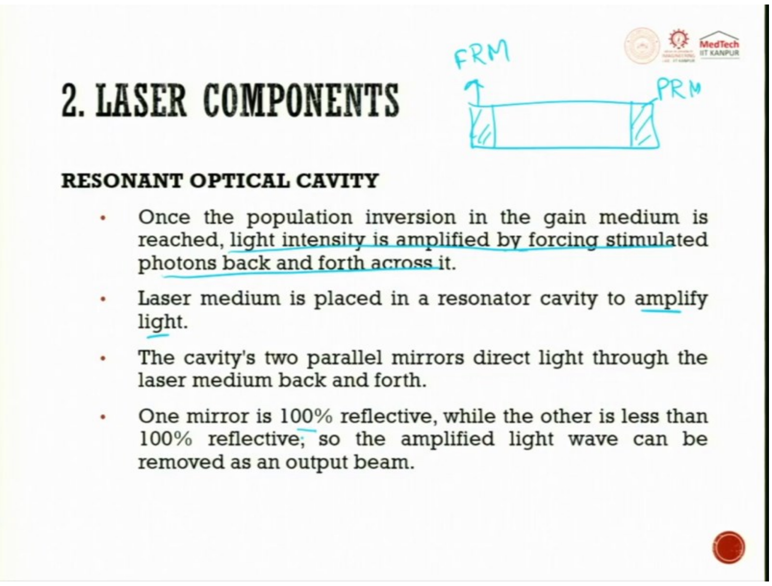

Once the population inversion in the gain media is reached, the light intensity is amplified by forcing stimulated photons back and forth across, that is why I told you there is a medium. So, this is fully reflecting mirror, this is partially reflecting mirror.

So, it amplifies inversion in the gain media, reaches the light intensity which is amplified by forcing back and forth movement of photons. The laser media is placed in a resonating cavity to amplify the light, the length of the resonating cavity is important which will try to dictate the amplification. The cavity has two parallel mirrors which direct light through the laser medium back and forth. So, one side is 100%, the other side is $<100\%$ to get the required output.

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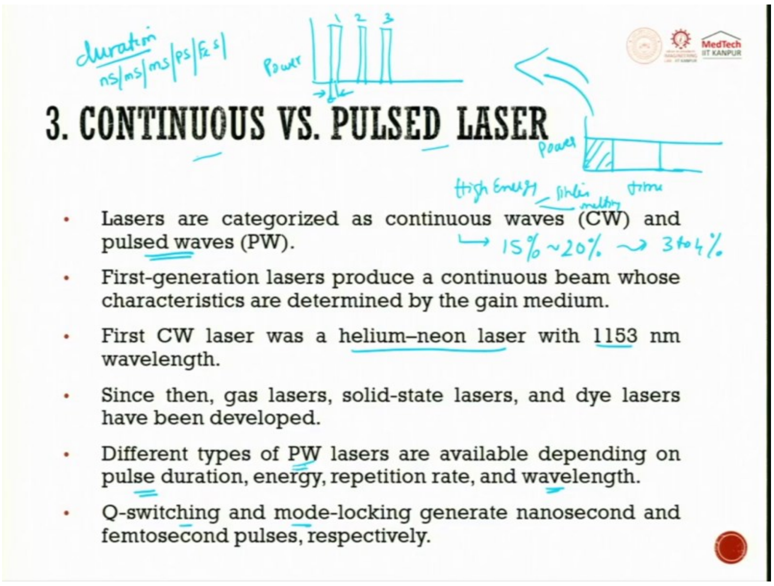

When we go to the next level of understanding of laser, we should try to understand what is continuous laser and what is pulsating laser. So, the continuous laser versus pulsating laser. Continuous means it is like this so, you have a constant power coming up this constant power. If you have a very high energy, then you can use it for sintering or melting but this is continuous. When we have a same laser but now what we do is we chop it off and we try to have the same energy here.

So, the same thing if I try to chop it same laser power, what do I do? I try to segment it and then I try to chop it. So, and then chop it and release it as instant. So, I have a very high power for a very short duration. Same thing I compress and I release same energy. So, the peak power will be very high but the average power for this also will be the same. So, this is where you get a very high peak power to melt. So, always we prefer to use a pulsating wavelength laser.

Continuous is also there, continuous is not so very energy efficient. Pulsating is energy efficient and here since it is only a small packet of energy of very high thing comes so, the circuit also need not be so robust that like that of continuous, and continuous after a certain peak power if you want to go, it becomes very inefficient.

Today the continuous laser we are talking about efficiency somewhere close to 15-20%. So, if you apply 1 kW energy you can get only 200 W of energy which is useful. which comes out of the laser, which will then get into the system, and then you do. So, finally the efficiency will go down to 3-4% only.

So, that is why people are now using pulsating laser. The first generation laser produced a continuous beam whose characteristics are determined by the gain media. What is the gain media? the material which is kept there. The continuous laser was helium neon laser which has a wavelength of 1153 nm. Since then gaseous laser, solid state laser, dye laser has been developed.

The different types of pulsed wave lasers are also available today depending upon the pulse duration. So, different types of pulsed wave lasers are available today in the market where it depends on pulse duration this is what it is it will be in ms.

Let me write down the durations, duration it can be in ns, ms, µs, ps and fs; all these things are the pulse duration we are talking about. Energies it can be in kW, repetition rate again it can be from 10 Hz it can go up to kHz.

When you go up to kHz, the power will go down when you have a lesser repetition rate you will have a higher pulse energy wavelength is also there. q switching and mode locking generates nano second and the femtosecond laser. These are mode lockings which tries to chop.

So, q switching and mode locking are other interesting concepts which we will see in the later part of the course and that helps you to chop. So, till now we have seen little bit fundamentals about laser.

So, we saw what is laser? what are the different types of laser? 2 level, 3 level, 4 level, what are all the basic construction of a laser? then what are the two different types of laser? We will continue in the next lecture to understand more on the laser parameters. Thank you very much.